The Technological Evolution of Robot-Assisted Surgery in Clinical Treatment: from Precise Control to Intelligent Integration

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Abstract. Nowadays, Robotic-assisted surgery (RAS) is highly mature and has been used in most of the surgical treatments. Compared to the history of clinical surgery, the surgical robot is only a small part of the whole history of clinical surgery. Still, it has proved itself to the world by its controllability and precision. This article aims to review the development history of the RAS by papers on Google Scholar, from the first surgery robot Arthrobot, the most famous robot Da Vinci robot system, to the recent robots like Natural Orifice Transluminal Endoscopic Surgery (NOTES) robot, and the combination of surgery robots with artificial intelligence (AI) and fifth-generation mobile communication technology (5G). The paper aims to review the history of RAS and discuss the future development and challenges of the surgery robots.

Keywords: Robotics, robotic-assisted surgery, history of surgery robot, technology.

1. Introduction

Nowadays, clinical surgery is the basis of the whole medical science; the first clinical surgery can be traced back to ancient Babylon and ancient Egypt. To pursue a higher success rate and reduce the harm to patients, the medical community first employed robots in surgical procedures. After that, the surgical robot has developed rapidly, especially over the past 20 years [1]. Until now, there are more than 30 surgical fields that have started to use surgical robots to do clinical surgery, and this number is continuing to increase over the years. Now the robotic-assisted surgery (RAS) has become a new surgery standard, but the technology of RAS was not as successful as it is nowadays in the beginning; it has experienced a quick and continuous development to reach today's accomplishment. This article aims to study the development of the RAS technology from 1980 to the 2020s by reviewing papers on Google Scholar (as shown in Figure 1), and discuss the future of the RAS technology.

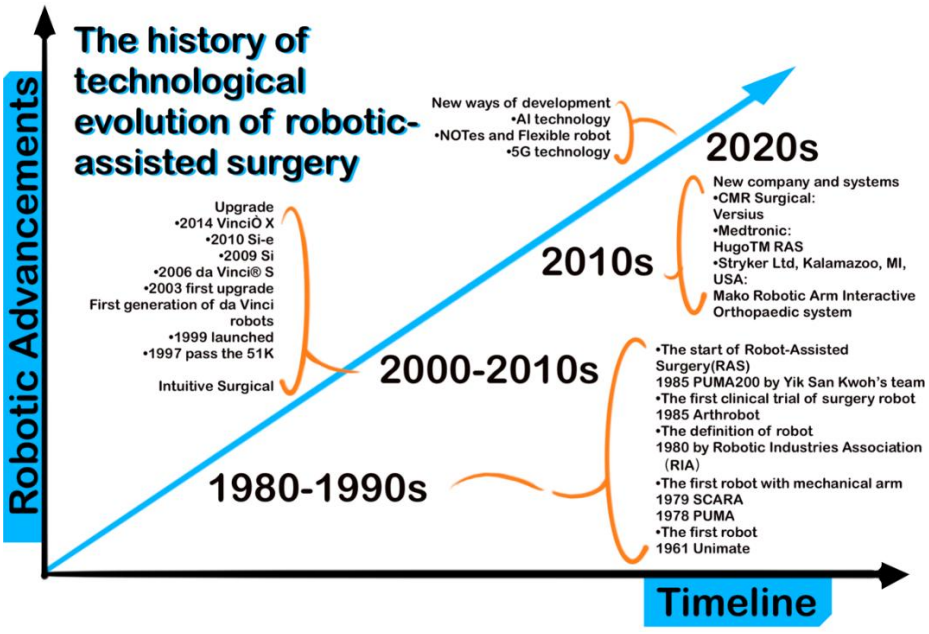


Figure 1. The history of technological of robotic-assisted surgery (Photo credit: Original)

2. The Beginning of Surgery Robots

2.1. From Concept to Reality

In the past, robots were only appearing in science fiction. Until 1961, Unimation company developed the first industrial robot—Unimate [2], and it was used in processing molten die-cast parts. This is the birth of the first industrial robot, and it also shows that high-risk and labor-intensive tasks can be performed by robots.

2.2. From Industry to Surgery

After Unimate, Programmable Universal Machine for Assembly (PUMA) and Selective Compliance Assembly Robot Arm (SCARA) were introduced in 1978 and 1979 respectively [3]. This is the first time a robot has appeared in the form of a robotic arm, and it also shows the changing of robot functions from a specific function to face multiple tasks. The appearance of PUMA and SCARA showed that the technology of robots is mature enough, paving the way for their entry into the surgery field.

In 1980, the Robotic Industries Association (RIA) released the first precise definition of robot: A reprogrammable, multifunctional manipulator designed to move material, parts, tools, or specialized devices through variable programmed motions for the performance of a variety of tasks.

The first clinical trial of a surgical robot took place in Vancouver, Canada, on 12 March 1985, when the first voice-controlled orthopedic surgical assistance system called Arthrobot successfully assisted the position of the knee joint [4]. On 11 April, Yik San Kwoh and his team used PUMA200 to perform a stereotactic biopsy on the patient. This process involves using a robot to secure the guide for the biopsy needle and put the biopsy needle into the brain of the patient. When the end effector is in position, the robot stops its power supply. This surgery pioneered the Robot-Assisted Surgery (RAS), and started the development era of surgery robots [4].

3. Da Vinci System

The Da Vinci robot, the most successful surgical robot, was invented by Intuitive Surgical [5]. The Da Vinci robot is an advanced laparoscopic system, and the main aim of it is to minimize the harm to patients while doing complex surgery, and this is also the main aim of other surgical robots. In 1997, the First generation of the Da Vinci robot passed the certification by the U.S. Food and Drug Administration (FDA). After 1 year, the first surgery system was developed for human use [1]. It included the functions of thoracoscopic internal mammary harvesting, mitral valve repair, cholecystectomies, and Nissen fundoplication.

In 1999, after undergoing plenty of tests, the first generation of the Da Vinci robot finally came on the market [6]. It has 3D Vision, EndoWrist® Instrument, it also fits the human body well, and can do surgery with high precision. Moreover, it overcame the longstanding obstacles hindering the advancement of laparoscopic radical prostatectomy (LRP).

In 2003, the Da Vinci robot was upgraded for the first time. To make it easier for clinical doctors to control, the fourth robotic arm has been added [6]. In 2006, the new system of the Da Vinci robot, called Da Vinci® S was introduced. It featured a multi-image display capability, which enabled high-definition visualization [6].

In 2009, the Da Vinci robot Si version was released, there was an additional console added to enable collaborative surgery. After a year, the Si-e version was released. The S-ie version is the basic edition, which only has three robotic arms. On April 1st of 2014, the Da Vinci® X system was approved by the FDA for distribution. It added an overhead arm and enables instruments and cameras to have greater mobility through ports [7].

After 10 years of development, the Da Vinci surgical robot has become the most powerful surgical robot in every aspect at that time, and no system can surpass it.

4. Break Monopoly and Develop Diversely

Due to the Da Vinci surgery robot and its powerful system, the surgical robotics market has been monopolized, and no system can surpass it. From 2007 to 2009, the number of Da Vinci surgery robots had increased nearly 75% in America. In 2009, Intuitive Surgical company reported revenue of $1 billion (increased 20% compared to 2008), and 1661 Da Vinci System had been installed globally [8].

This monopoly persisted until 2010. After 2010, the technology of surgical robots was highly mature, and there was a huge, underdeveloped market for surgical robots. So, surgery robots are springing up like mushrooms after rain. To break the monopoly made by Intuitive Surgical, and let the surgery robot develop diversely, surgery robots found two new dimensions to develop, which are specialization and multifunctionalization, changing the aim of the surgery robot from universal applicability to intelligence like Hugo™ RAS System and Mako robot.

CMR Surgical (Cambridge, UK) has developed the Versius platform [9]. It is a remote-control system for surgery robots, including an open-style console and high-definition 3D glasses. There are also multiple bedside armrest cart units to provide superior surgical planning for doctors. Compared to the Da Vinci robot, the Versius system is smaller and portable; it also adds human-like wrist joints with seven degrees of freedom on its arms to imitate the human arm. This decreased the study time for doctors and the land area. Moreover, the Versius platform specializes in portable and affordable, so it fits better for small and medium operating rooms.

Based on the idea from CMR Surgical, Medtronic (USA) has developed the Hugo™ RAS System. It consists of one console, one system tower, and four independent robotic arm vehicles. Hugo™ RAS System is a good example of a multifunctional surgical robot. Due to the modular design, Hugo™ RAS System is more flexible and can provide doctors with a more comfortable and personalized work environment; it also costs less and is easier to upgrade [10].

For orthopedic surgery, the Mako Robotic Arm Interactive Orthopaedic system (Stryker Ltd, Kalamazoo, MI, USA) is an outstanding system. It specializes in total knee arthroplasty (TKA) surgery treatment. Its robotic arms have visual, tactile, and audio sensors to give feedback, which helps the doctor to have more precise control over the saw blade when cutting the bones [11]. If the patient exhibits convulsive movements during surgery, the machine will automatically detect this and stop to prevent further harm to the patient. Compared to the Da Vinci surgery robot, the Mako robot based on CT technology, is more focused on planning and precise motion. It has evolved from an auxiliary tool to a surgical assistant.

In conclusion, the surgery robots in the 2010s were more focused on portable and flexible platforms like the Versius platform and Hugo™ RAS, some of them specialized in a specific function like the Mako system. Although they have different ways to develop, they all showed a trend that surgical robots are more intelligent and can be surgical assistants for doctors.

5. The Future of Intelligence and Autonomy

Nowadays, surgical robots are advancing comprehensively in the medical field, but they cannot analyze the situation and give opinions to doctors by themselves, so surgical robots are still tools for doctors. The emergence of artificial intelligence (AI) can help to solve these issues. When surgery robots combine with AI, they will be more intelligent and more like surgical assistants.

AI technology can study, deduce, and make decisions without specific coding. Since 2020, many technologies have developed quickly because of AI (for example, the Natural Language Processing field, Computer Vision, and Autonomous Driving), also in the surgical robotics field, AI has also participated in and replaced some of the functions of a doctor's eyes and brain [12]. Until now, AI algorithms have been able to identify anatomical structures in surgical videos in real time and highlight them. Shunjin Ryu and his team collected videos of ten patients undergoing laparoscopic left hemicolectomy and rectal resection from November to December 2022 and compared whether doctors or people trained in AI navigation (AIN) could identify nerves [13]. The conclusion is that

AI has improved the ability of trained people to identify nerves a lot. This also demonstrates that AI can assist doctors with observation during surgical procedures, and it can also replace some functions of the surgeon's eyes.

In 2020, AI technology has shown the potential for collaboration with computer-assisted surgical planning (CASP) [14]. CASP can build a three-dimensional virtual model of the patient's anatomical structure on a computer. AI can combine well with CASP, because CASP can provide AI with a comprehensive database to analyze and learn. After this, AI technology can help doctors assess risks before surgery and choose the safest strategy to minimize the harm to patients. Although this technology has not entered clinical research yet, there is no denying that doctors can reduce a lot of their workload after AI is combined with CASP, and the AI can then replace part of the surgeon's brain.

To make AI decide, there needs to be a database for AI to learn and estimate the situations in surgery. In 2004, researchers in the field of computer-assisted surgery (CAS) had elucidated that there needs to be a common standard for all the surgeries [15]. Nowadays, the field of Surgical Data Science (SDS) is recording surgery data like videos, robotic arm movement, patient vital signs, and they analyze and model these into a common standard. This common standard can also be used in AI, which AI can plan surgery based on each patient by this standard, and predict the risks and aftereffects, truly achieving treatment specifically for each patient's situation. After the combination, AI in surgery robots will not just act as a surgery tool, but also as a surgical assistant to help with planning and give opinions.

While achieving software intelligence through AI, hardware upgrading in surgical robots is also important. To achieve the aim of minimizing harm to the patient, the Natural Orifice Transluminal Endoscopic Surgery (NOTES) robot has emerged. NOTES robot is different from all other surgery robots; it can do surgeries through natural orifice transluminal like the oral cavity, rectum, and vagina. During the surgery, it has high surgical performance and does not leave any wounds on the patient. NOTES represents the ultimate form of minimally invasive surgery. Although NOTES has many advantages, it also faces lots of challenges, like how to put the robotic arm in a natural orifice transluminal, how to image, and how to do multiple things with only one robotic arm. Nowadays, major healthcare companies are all seeking solutions to solve the issue. Verb Surgical is a robotics company established in 2015 by Google and Johnson & Johnson [16]. This company aims to use a surgical robot to do the whole surgery independently. They integrated AI into their robotic system and provided doctors with an additional feedback system. This also emphasizes that AI can be a useful tool to NOTES, and to solve some of the intelligent problems.

Another challenge NOTES robot faces is how to do complex surgery in the winding and twisting natural orifice transluminal. Flexible robotic technology is a good technology to solve this issue. 40 years ago, flexible robotic technology had already been used in Minimally Invasive Surgery (MIS) [17]. The flexible robot has a robotic arm with multiple flexible joints to help go through the natural orifice transluminal. So, the flexible robot can reach specific places in the natural orifice transluminal, which other robots cannot reach [17]. The flexible robot has demonstrated perfect compatibility with the NOTES robot, and it has already been a part of the NOTES robot. To perform complex surgeries in the natural cavities, researchers have also broken the whole surgery system into small modules and sent multiple accessory instruments (scissors, graspers, biopsy forceps) into natural body cavities, enabling multifunctional surgical procedures without causing extra trauma to the patient [18]. Above all, NOTES has turned the definition of the RAS from open surgery into an entirely new surgical paradigm. NOTES focused on an absolutely different path compared to the Da Vinci surgery robot, it is trying to find a way to do surgery without causing harm to the patients, and it is truly a next-generation technology.

Hardware and software like NOTES robot and AI technology are important for surgery robots, but surgery robots still need doctors to control them during surgery. In some remote areas that do not have doctors to do robotic surgery, it costs plenty of time for doctors to arrive and do surgery, so distance is really an issue in surgical treatment. Nowadays, the fifth-generation mobile

communication technology (5G) has high-speed and low-latency, and it has been rapidly used in many fields. Its air interface achieves an extremely low latency of only 1 millisecond, fully enabling the requirements of remotely controlling surgery robots. So, if the 5G technology is combined with surgical robots, the distance issue will be solved. Until now, several countries have already deployed 5G networks, and because of the success of surgery robots, many countries have already used 5G to control surgery robots remotely [19]. In December of 2018, China's Huawei Technologies and China Unicom performed a 48-kilometer-long pig liver resection using the Kando robotic surgery system [19]. This proves the usage of 5G in robotic surgery is stable and fits RAS well. In summary, 5G technology will enable surgical robots to perform remote surgeries regardless of distance limitations. In the future, doctors will not just perform a single operation at a time, but they will also perform multiple surgeries at the same time, in different places. This will maximize medical resources, enabling more patients to receive the best possible treatment. However, internet security and legal issues are still issues that need to be solved, and researchers must continue to tackle network latency challenges.

6. Conclusion

The development of surgical robots follows the process of changing from a tool to a smart assistant, but not a simple technology iteration. This article aimed to describe the development history of RAS. Surgery robots like the PUMA system turn the concept of surgery robots into reality, the Da Vinci System has achieved technological platformization and popularization, and in recent years, surgery robots are increasingly becoming intelligent because of AI. Despite the RAS being mature nowadays, the evolution of RAS is far from over; there are still issues to be solved. The Versius platform showed a trend to decrease the cost, but the RAS treatment is still expensive until now, and the NOTES robots also have space to improve. In the future, surgery robots may combine with technologies like AI and 5G to provide a safer and more reliable surgical assistance for doctors and patients.

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